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## Ice magnetization in the EPICA-Dome C ice core: Implication for dust sources during glacial and interglacial periods

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[1] Isothermal remanent magnetization and insoluble dust content of ice samples from EPICA-Dome C ice core were measured to characterize the magnetic properties of atmospheric dust. Despite the larger concentration of dust aerosol during glacial stages, the magnetization of the dust fraction was found to be higher during interglacials and exhibits a larger variability. Changes in magnetic mineralogy of aerosol dust in ice from different climatic stages were also characterized using coercivity of remanence. Variations of magnetic properties of dust from glacial to interglacial stages indicate changes in dust provenance, in agreement with previous results based on geochemical analysis. However, the extremely large magnetizations of some interglacial samples also suggest that episodic eolian deposition from highly magnetic deposits occurred during interglacial periods.

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### 1. Introduction

[2] Atmospheric dust contains a significant fraction of highly magnetic iron oxides that are common terrigenous minerals. The minute amount of atmospheric dust included in ice cores can carry a laboratory-induced Isothermal Remanent Magnetization (IRM), which can be precisely measured directly in ice samples [Lanci *et al.*, 2004; Lanci and Kent, 2006]. Although their nature limits the type of experiments that can be made on ice samples [Lanci *et al.*, 2001], the concentration of the magnetic dust fraction in polar ice, and to a lesser extent its mineralogy, can be estimated through standard magnetic methods such as those used in environmental magnetism [e.g., Evans and Heller, 2003]. This information on a novel property of ice allows us to investigate a new physical property of the atmospheric aerosol deposited in polar regions.

[3] A portion of the ice IRM carried by nanometric-sized particles can be explained as fallout of meteoric smoke [Lanci and Kent, 2006; Lanci *et al.*, 2007] that originated from atmospheric ablation of meteorites and micrometeorites at high (~100 km) altitude and transported in the stratosphere over the winter pole by atmospheric circulation. The magnetization of coarser magnetic particles, which produce a stable saturation IRM [Lanci and Kent, 2006],

has been successfully correlated with dust concentrations from interglacial to glacial periods in the North-GRIP ice core (Greenland) and interpreted as due to terrigenous sources. In Greenland ice, where the magnetic properties of aerosol dust do not change noticeably from glacial to interglacial times, the average IRM of dust (IRM<sub>DUST</sub>), computed as the slope of the linear regression of ice IRM versus dust concentration, was found comparable to the IRM of Chinese loess [Lanci *et al.*, 2004]. Alternatively, if the magnetic properties of aerosol dust vary with time, IRM<sub>DUST</sub> can be computed from measurements of IRM and dust concentration for each sample.

[4] The concentration and mineralogy of magnetic minerals in terrigenous dust differ depending on the type of source rock and possibly the atmospheric transportation processes. Hematite  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub>, and magnetite Fe<sub>3</sub>O<sub>4</sub> (with perhaps maghemite  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>) are the most common and chemically stable magnetic minerals in continental source rocks. These minerals are likely to constitute the main carriers of remanent magnetism in polar ice and can be distinguished on the base of their magnetic properties. Hematite has a very high magnetic coercivity but a very low spontaneous magnetic moment (hence, low remanent magnetization) compared to the moderate coercivity and high spontaneous moment of magnetite or maghemite (which we consider indistinguishable based on magnetic measurements performed on ice samples). The high coercivity of hematite can thus be used to identify its presence in a sample whereas magnetite/maghemite because of their high magnetic moments are often the main carriers of remanent magnetization even if they are present in small concentration.

[5] In this paper we characterize glacial and interglacial aerosol dust from the EPICA-Dome C ice core from East Antarctica by measurements of IRM and coercivity of

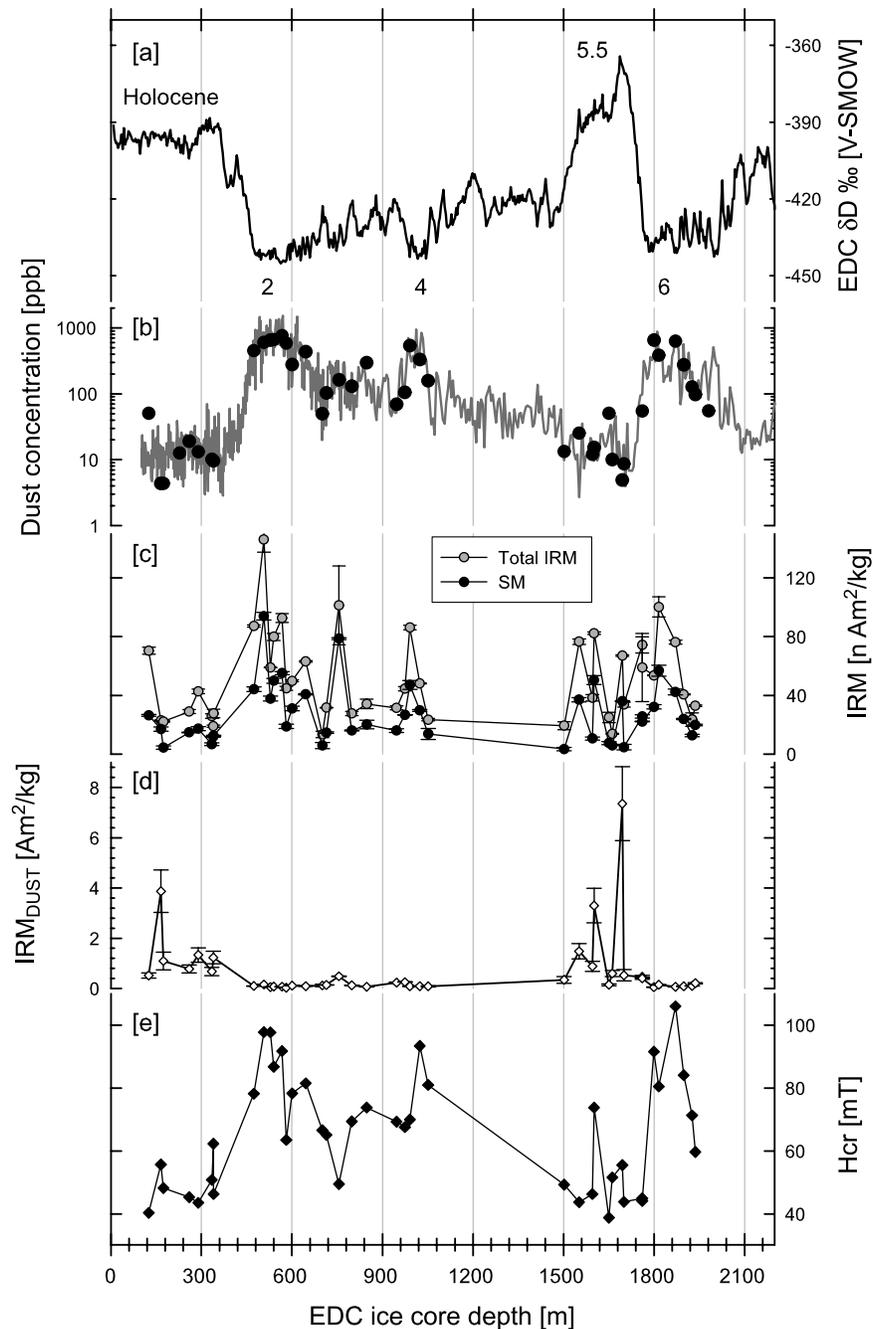
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**Figure 1.** Summary of magnetic and dust measurements from EPICA-Dome C ice core records. (a) Stable isotope [EPICA Community Members, 2004]; (b) mineral dust concentrations [Delmonte et al., 2004]. Circles indicate dust concentrations in samples measured in this work and for which magnetic properties have been measured on adjacent samples; (c) total and stable magnetization (SM) of ice samples; (d) dust magnetization ( $IRM_{DUST}$ ) and (e) coercivity of remanence (Hcr).

remanence (Hcr) on ice samples and discuss the implications of these magnetic properties for dust provenance.

## 2. Materials and Methods

[6] We investigated 41 ice samples from the EPICA-Dome C ice core (East Antarctica;  $75^{\circ}06'S$ ,  $123^{\circ}21'E$ ) [EPICA Community Members, 2004]. Samples were select-

ed from an interval spanning from 136 m depth (Holocene) to 1936 m depth corresponding to marine isotope stage (MIS) 6 (Figure 1a). Ice samples about 5–7 cm long were cut and decontaminated at LGGE-CNRS in a clean room (class 10,000) using standard procedures [Delmonte et al., 2004]. Two adjacent ice specimens were taken from each level, one for dust concentration analyses and the other for magnetic measurements.

[7] The IRM acquisition and measurement procedure is equivalent to that described by Lanci and Kent. [Lanci and Kent, 2006]. IRMs were induced in whole-ice samples at liquid nitrogen temperature (77 K) using a pulse magnetizer and measured immediately after to minimize rewarming using a 2G superconducting magnetometer with DC-SQUID sensors at the ALP laboratory. An IRM in a maximum field of 1T was first induced in the samples; subsequent IRMs were induced in the opposite direction with stepwise increasing fields to allow calculation of the  $H_{cr}$ , which is defined as the magnetic field able to nullify the remanent magnetization of a previously saturated sample.  $H_{cr}$  measurements consist of inducing a saturation IRM and measuring the resultant remanent magnetization after stepwise backfield IRM acquisition; the exact field value of  $H_{cr}$  is interpolated between zero-crossing IRM values. The maximum IRM was also remeasured after allowing the sample to reequilibrate to the freezer temperature ( $-20^{\circ}\text{C}$ ,  $\sim 256\text{ K}$ ) for about 24 h; the increase in temperature from 77 K to 256 K causes thermal relaxation of the remanent magnetization carried by very small magnetic particles [e.g., Dunlop and Ozdemir, 1997], thereby decreasing the remanent magnetization. The fraction of magnetic particles whose remanent magnetization relaxes at freezer temperature is referred as superparamagnetic (SP); the IRM carried by the SP fraction is simply calculated as the difference between magnetic measurements taken before and after thermal relaxation. We refer to the fraction of IRM that remains after warming to 256 K as the stable magnetization (SM) to distinguish it from the total IRM, which includes the SP fraction (thus  $\text{SP} = \text{IRM}_{\text{total}} - \text{SM}$ ).

[8] Insoluble dust concentration (IDC) and size measurements were performed with a Coulter Multisizer II, which can detect insoluble material with equivalent spherical diameters of 1 to 31  $\mu\text{m}$ . The dust mass was calculated assuming that grains have an average density of 2.5  $\text{g}/\text{cm}^3$ . Average dust concentrations are 18 ppb for the Holocene and 610 ppb for the LGM, and 22 ppb and 300 ppb for interglacial MIS 5.5 and glacial MIS 6, respectively. As shown in Figure 1b, these values are in good agreement with previous measurements on EPICA ice samples [Delmonte et al., 2004].

[9] The magnetization of the dust fraction ( $\text{IRM}_{\text{DUST}}$ ) is calculated by dividing SM by IDC (i.e.,  $\text{IRM}_{\text{DUST}} = \text{SM}/\text{IDC}$ ) and is thus affected by errors in both measurements. The resultant error ( $\Delta_{\text{IRM}_{\text{DUST}}}$ ) can be relevant especially for samples with low dust concentration or weak magnetization; therefore, we estimate the analytical error ( $\Delta_{\text{IRM}_{\text{DUST}}}$ ) as the root mean square of the sum of the squares of the two relative errors of the measured variables, i.e.,

$$\Delta_{\text{IRM}_{\text{DUST}}} = \text{IRM}_{\text{DUST}} \cdot \text{sqrt}\left(\left(\Delta_{\text{SM}}/\text{SM}\right)^2 + \left(\Delta_{\text{IDC}}/\text{IDC}\right)^2\right)$$

SM of each sample was computed as the mean of 3 independent measurements and its analytical error ( $\Delta_{\text{SM}}$ ) was taken as the largest difference between the measurements and the mean value. The analytical error of IDC ( $\Delta_{\text{IDC}}$ ) was taken as 20% for samples with dust concentrations of about 1000 particles/g typical of interglacial samples, and 2% for glacial samples with high dust

concentration of 50,000 particles/g, in accord with [Delmonte et al., 2002].

### 3. Results

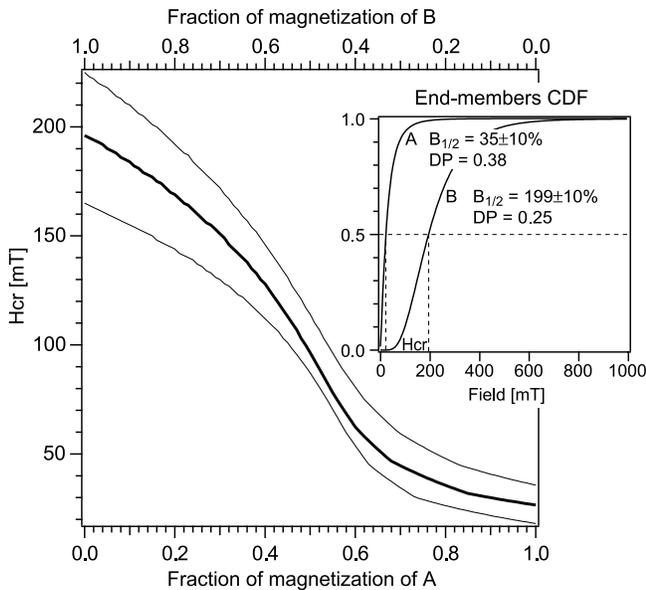
[10] A summary of magnetic and dust concentration measurements on ice samples from the EPICA core is shown in Figure 1. As observed in the Vostok ice core [Lanci and Kent, 2006] and to a lesser extent in North-GRIP ice core [Lanci et al., 2004], the ice from EPICA also shows a considerably large SP magnetization, which can even be larger than SM in interglacial periods. At least part of this SP magnetization has been interpreted as due to fallout of meteoric particles of nanometric size [Lanci and Kent, 2006; Lanci et al., 2007]. Since we are looking to find variations in terrestrial dust provenance, we calculate  $\text{IRM}_{\text{DUST}}$  using SM, which is carried by the fraction of magnetic grains larger than  $\sim 20\text{ nm}$  [e.g., Dunlop, 1973; Lanci and Kent, 2003] and is thus not strongly affected by the background of meteoric fallout.

[11] The IRM of EPICA ice (Figure 1c) generally shows highest values corresponding to glacial periods (Figure 1a) with high dust concentrations (Figure 1b), which is expected as ice IRM is carried by the dust mineral load. More surprisingly the  $\text{IRM}_{\text{DUST}}$  revealed a large change between glacial and interglacial periods with the latter being characterized by higher  $\text{IRM}_{\text{DUST}}$ . Even disregarding the 3 outlier samples at 165.83, 1601.33, and 1694.83 m depth, which show extremely high magnetizations as well as large associated errors, interglacial dust is about 10 to 40 times more magnetic than glacial dust (Figure 1d). The change of  $\text{IRM}_{\text{DUST}}$  indicates a varying concentration of magnetic minerals in insoluble dust and thereby implies that the source of the aerosol changes in different climatic stages.

[12] The extremely high  $\text{IRM}_{\text{DUST}}$  values in samples at 165.83, 1601.33, and 1694.83 m probably exceed even the magnetizations of possible volcanic source rocks and are difficult to explain. Although our measuring procedure is robust enough to consider a laboratory contamination to be very unlikely, the possibility of a different source of contamination of the samples, such as drilling fluids, cannot be entirely excluded. However, if such high concentration of magnetic minerals is attributed to natural material this is likely to be dust enriched in the heavier iron minerals such as continental placer deposits.

[13]  $H_{cr}$  is another property of dust that changes significantly between glacial and interglacial samples (Figure 1e). This is a convenient parameter to characterize the magnetic coercivity of a sample and is in fact expected to approximate the median of the coercivity distribution, which corresponds also to the field needed to achieve 50% of the maximum IRM (Figure 2). When there is a mixture of two different magnetic minerals in a sample,  $H_{cr}$  does not vary linearly with the remanence carried by the two phases; however, if the coercivity distribution of the two end-members is known it is possible to calculate the  $H_{cr}$  of the mixture as the median of the sum of the two end-member distributions.

[14] We attempt to make a semiquantitative mixing model for  $H_{cr}$  to estimate the variation of magnetic mineralogy between two end-members, which we assume are hematite and magnetite/maghemite. The model computes the varia-



**Figure 2.** Hcr versus the fraction of remanence carried by end-members A (magnetite sample MagB2) and B (hematite sample AH1) taken from [Robertson and France, 1994]. DP and  $B_{1/2}$  indicate the dispersion parameter and median field parameter, respectively. Thin lines show the variability of the model with 10% changes in  $B_{1/2}$ . The inset shows the cumulative distribution function of the end-members, which approximate their IRM acquisition curves, and illustrate graphically Hcr.

tion of Hcr in a system with 2 different magnetic phases (end-member minerals) while changing their relative contribution to remanence. Following Robertson and France [Robertson and France, 1994], we make the simplistic, but reasonable, assumption that each of the magnetic phases has a lognormal coercivity distribution. Hcr is thus computed numerically as the field corresponding to the median value of the sum of two end-member distributions multiplied by their contribution to the total remanence which sums up to unity:

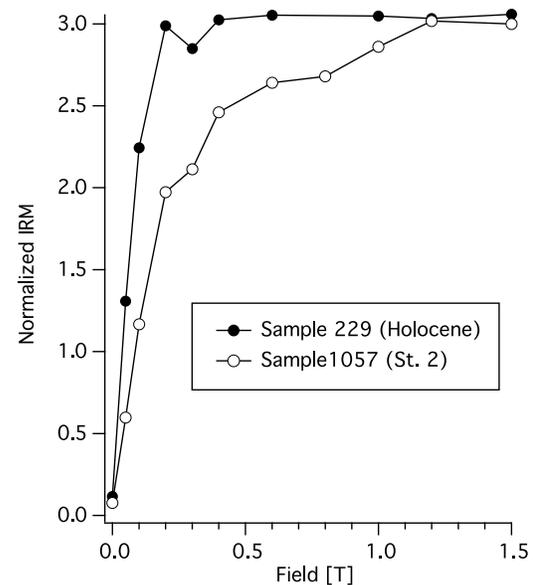
$$\text{Hcr} = \text{median}(\text{Frac}_A \cdot \text{LN}_A(H) + \text{Frac}_B \cdot \text{LN}_B(H))$$

where  $\text{LN}_{A,B}(H)$  are the lognormal distributions of end-members A and B, and  $\text{Frac}_{A,B}$  are their mixing fractions with  $\text{Frac}_B = 1 - \text{Frac}_A$ .

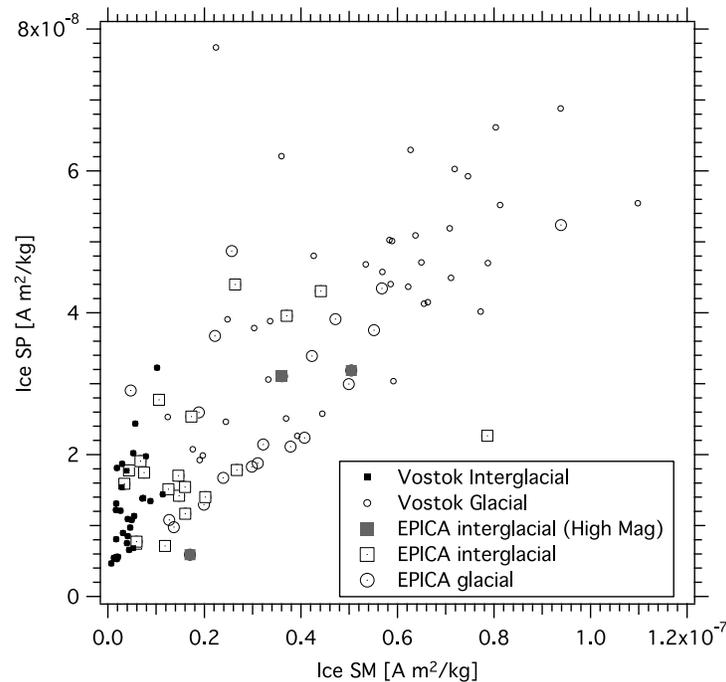
[15] End-member distributions were chosen starting from the experimental values of the median field and dispersion parameter for synthetic magnetite (MagB2) and hematite (AH1) samples of Robertson and France [Robertson and France, 1994]. Furthermore, their results on IRM acquisition in natural materials suggest a small variability of the dispersion parameter and a larger variability in the median field. We computed a mixing model using the MagB2 and AH1 parameters and tested its sensitivity for different median fields of end-members with constant dispersion parameter. Numerical results show that the Hcr value is quite sensitive to the median field of the end-member coercivity distributions, although the shape of the Hcr

mixing curve does not change significantly for reasonable values of end-member distribution parameters. This means that given a measured Hcr the relative contribution (in remanence) of the two end-members is subject to the uncertainty of the end-member parameters as shown in Figure 2. Within the limitations explained above (i.e., assumption of lognormal coercivity distribution and uncertainty of the parameters of end-members distribution), the model gives quantitative results that translate the Hcr values to the fraction of remanence carried by the two end-members. Even though the absolute value of the fraction is sensitive to end-member parameters the results are still useful to compare different ice samples where end-members presumably remained the same.

[16] In EPICA ice samples, Hcr values follow relatively well the IDC with interglacial samples having consistently lower Hcr than glacial ones, suggesting that the latter have a larger concentration of high-coercivity minerals. This observation is in agreement with results from IRM acquisition curves of typical glacial and interglacial ice samples (Figure 3). These data show that IRM magnetizations of interglacial samples saturate at inducing fields of about 0.2 T, as expected for magnetite/maghemite-bearing dust, whereas glacial samples are not saturated at the maximum field of 1.5 T, suggesting the presence of a large amount of hematite. However, it should be recalled that the backfield IRMs were measured at low temperature with no relaxation and therefore include the SP contribution of extraterrestrial origin.



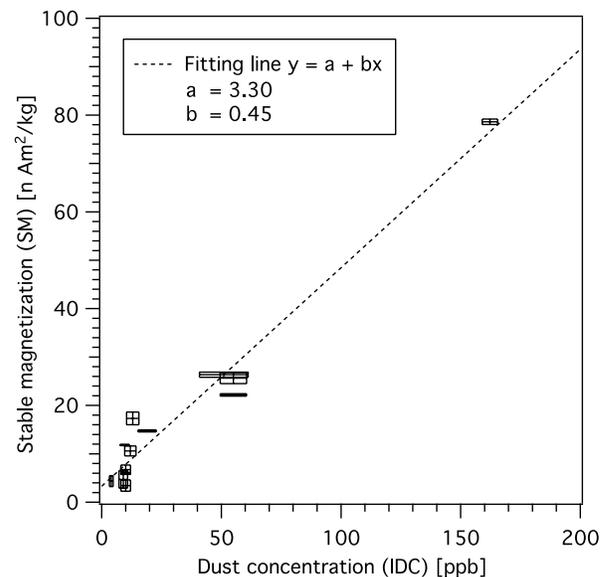
**Figure 3.** IRM acquisition curves for representative samples of glacial and interglacial stages from the EPICA ice core. The absolute values of magnetization are normalized with respect of the standard deviation. Interglacial ice sample (closed symbols) saturates by 0.3 T, which is compatible with magnetite or maghemite. Glacial ice sample (open symbols) shows higher coercivity and does not saturate at the maximum field of 1.5 T, suggesting it contains hematite.



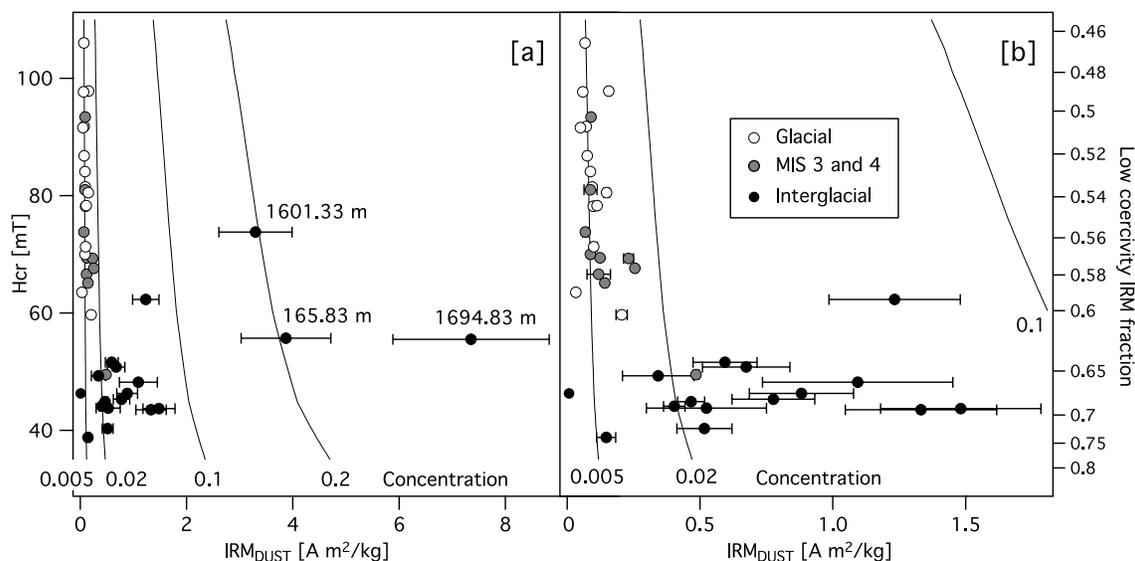
**Figure 4.** Stable (SM) versus superparamagnetic (SP) ice magnetization in EPICA and Vostok samples. Glacial samples from the two sites have the very similar values of magnetizations while interglacial samples from EPICA generally have a larger magnetization compared to Holocene samples from Vostok; moreover, several interglacial ice samples from EPICA show a magnetization comparable to that of glacial ice despite the lower dust concentration. The 3 outlier samples with extremely large dust magnetization (at 165.83, 1601.33 and 1694.83 m depth) are plotted with grey square symbols.

[17] We noticed no significant difference between the magnetic properties of interglacial samples from the Holocene and those of samples from MIS 5.5. Glacial samples from the LGM and MIS 6 also have virtually identical magnetic properties. Comparison of IRM of ice samples from Vostok [Lanci *et al.*, 2007] and EPICA cores shows a rather similar SP/SM ratio and similar absolute values for SM and SP magnetizations (Figure 4). Nevertheless, even though the IRMs of glacial samples from the two sites are virtually identical, the IRM of interglacial samples from EPICA is generally larger than interglacial samples from Vostok, with a few EPICA interglacial samples showing IRM similar in magnitude to glacial samples. Such a difference between similar sites, which is most probably related to a different concentration of magnetic minerals in ice deposited during warm climatic stages, is surprising and suggests that, at least during interglacial times, the deposition of aerosol dust has a significant geographical variability.

[18] A linear correlation of SM and IDC, similar to that found in Greenland [Lanci and Kent, 2006], is also expected in EPICA ice core, provided a set of samples with uniform magnetic mineralogy is selected. Such a subset of EPICA samples was selected based on chosen values of  $H_{cr}$  in the range from 40.3 to 51.6 mT to ensure a uniform magnetic mineralogy. Unlike the ice from North-GRIP, where magnetic properties of aerosol dust do not change significantly from glacial to interglacial times [Lanci *et al.*, 2004], the selected EPICA samples come only from interglacial stages with the only exception of one sample from MIS 3.



**Figure 5.** Correlation between ice SM and IDC for a subset of EPICA samples with  $40.3 \text{ mT} \leq H_{cr} \leq 51.6 \text{ mT}$ . The best fit line goes to the origin within a small error compatible with the laboratory noise level of  $4 \times 10^{-9} \text{ A m}^2/\text{kg}$  estimated by Lanci *et al.* [Lanci *et al.*, 2004]. The average  $\text{IRM}_{\text{DUST}}$  for these subset of samples, deduced from the slope of the best fit line, is  $0.45 \text{ A m}^2/\text{kg}$ . The dimensions of the plot symbols represent the estimated measurement error in both axes.



**Figure 6.** Coercivity of remanence ( $H_{cr}$ ) plotted versus dust-IRM ( $IRM_{DUST}$ ) for EPICA ice samples. Samples have been divided into interglacial (including Holocene isotopic stages 5; open symbols), glacial (isotopic stages 2 and 6; closed symbols) and intermediate (isotopic stages 3 and 4; grey symbols) populations.  $H_{cr}$  mixing lines from the computed model are reported for different mass-concentrations of magnetic minerals, which for this purpose we assume a remanent magnetization  $M_r = 30 \text{ A m}^2/\text{kg}$  for magnetite and  $M_r = 0.2 \text{ A m}^2/\text{kg}$  for hematite. The vertical scale on the right is computed according to the  $H_{cr}$  model. Details without the 3 outlier samples are better shown in Figure 6b with the expanded horizontal scale.

Nevertheless, the results (Figure 5) confirm the direct relationship between SM and IDC as previously observed in North-GRIP [Lanci and Kent, 2006].

#### 4. Discussion and Conclusions

[19]  $IRM_{DUST}$  and  $H_{cr}$  are intrinsic properties of aerosol dust that show marked differences between glacial and interglacial times; these magnetic properties in EPICA ice samples are summarized in Figure 6. The different magnetic properties of glacial and interglacial samples are clearly indicated by their different clustering with some overlapping due to samples from intermediate climatic stages (MIS 3 and 4). The largest concentration of magnetic minerals as well as its variability in interglacial samples are also quite evident.

[20] Different source regions for Antarctic aerosol dust from glacial to interglacial times were previously established primarily by comparing the geochemistry ( $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $^{143}\text{Nd}/^{144}\text{Nd}$ ) of dust extracted from Antarctic ice with that of fine-grained mixed sediments from Southern Hemisphere potential source areas [e.g., Delmonte et al., 2004, 2007]. The results from magnetic measurements also support different dust provenances. We found that low  $H_{cr}$  and large  $IRM_{DUST}$ , which are often expected in dust originating from soils or volcanic terrains, characterize interglacial samples; in contrast, glacial samples have high  $H_{cr}$  and low  $IRM_{DUST}$ . More information on dust provenance might be gathered with further magnetic measurements on possible source area samples, which are needed to help establish dust provenance and its variability during interglacial intervals.

[21] A major novelty that arises from magnetic measurements on ice is the large variability of  $IRM_{DUST}$  within the

interglacial stages; such large mass magnetizations are unusual in crustal rocks. We suggest that placer deposits enriched in higher density dust particles such as iron oxides, could constitute possible source areas that were active in interglacial times. The geographic variability of highly magnetic interglacial dust episodes suggested by the comparison of EPICA and Vostok ice is a second interesting observation that results from this study. Local variability of dust deposition favors the hypothesis that the source of high magnetic dust is located near the deposition area, e.g., the Ferrar Dolerite in the Transantarctic Mountains, or local meteorite fields in Victoria Land [e.g., Delisle and Sievers, 1991]. These conclusions, which suggest the presence of local sources of particulates active during interglacials, are not necessarily in contrast with the evidences for distal sources suggested by Sr/Nd isotopes geochemistry. The more temporally discrete magnetic measurements can detect rapid variations that could be averaged out by Sr/Nd isotopes measurements which require very large samples of ice. More importantly, the geochemical and magnetic methods are sensitive to very different properties of dust and thus are more likely to be complementary rather than alternative provenance methods.

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